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Current status and perspectives of the LUCIFER experiment

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Abstract

The quest for Neutrinoless Double Beta Decay (0νDBD) represents one of the most promising ways to investigate the neutrino mass nature, Dirac or Majorana. A convincing detection claim demands for detectors with excellent energy resolution and almost zero background in the energy region of interest. These features can be obtained with the approach of the LUCIFER project, funded by an European grant, which is based on the double readout of the heat and scintillation light produced by ZnSe scintillating bolometers. The resulting identification and rejection of the α interactions, as well as the large Q-value of the emitter, will guarantee a background lower than 10^{-3} counts/keV/kg/y in the energy region of the 0νDBD of ^{82}Se, an order of magnitude lower with respect to the present generation experiments. Despite the small mass of ~17 kg, LUCIFER will reach a 90% CL sensitivity of 0.6×10^{26} y on the half-life of the decay.
We describe the current status of the project, including results of the recent R&D activity.

Keywords: Neutrinoless double-beta decay, Scintillating Bolometers, ZnSe, LUCIFER

1. Introduction

In the last decade much progress has been made in neutrino physics. Oscillation experiments created a clear picture of this elusive particle and we are now entering the era of precision measurements. Nonetheless, some of its fundamental properties, like nature (Dirac or Majorana) and mass (absolute scale and hierarchy), are still unknown. At present, the most sensitive way to probe the neutrino nature is to search for the neutrinoless double beta decay.

The double beta decay with neutrino emission ($2\nu\beta\beta$) is the rarest nuclear decay ever observed in nature [1], in which two neutrons decay in two protons, two electrons and two antineutrinos. This is a second order weak transition allowed by the Standard Model (SM), with lifetimes ranging from 10^{18} to 10^{22} years [1]. Neutrinoless double beta decay ($0\nu\beta\beta$) is an hypothetical double beta decay in which no neutrinos are emitted. $0\nu\beta\beta$ is SM forbidden and can occur only if neutrino is a Majorana particle and would violate by 2 the lepton number conservation. The possible observation of this decay would also give an answer to the absolute mass scale question, since it depends on the neutrino Majorana mass. No lifetimes have ever been measured, only lower limits of the order of 10^{25} y [2].

The experimental signature of the $0\nu\beta\beta$ is extremely clear: two electrons emitted back-to-back, with a total energy equal to the Q-value of the reaction. $2\nu\beta\beta$ spectra are continuous, while $0\nu\beta\beta$ ones should present a single peak at the Q-value, as showed in Fig.1. FIGURAAAA

The extremely high lifetimes determine huge experimental challenges: in order to have chances to observe the $0\nu\beta\beta$ peak, it is mandatory to have a consistent detector mass (at least of the order of $100 \div 1000$ kg), to maximize the number of $\beta\beta$ emitters, and a very low background in the region of interest (ROI), to minimize the spurious events. Another fundamental requirement to fulfill is a good energy resolution, to discriminate the $0\nu\beta\beta$ peak from the right tail of the $2\nu\beta\beta$ distribution (as one can see by looking at Fig.1).

The sensitivity of an experiment is defined as the

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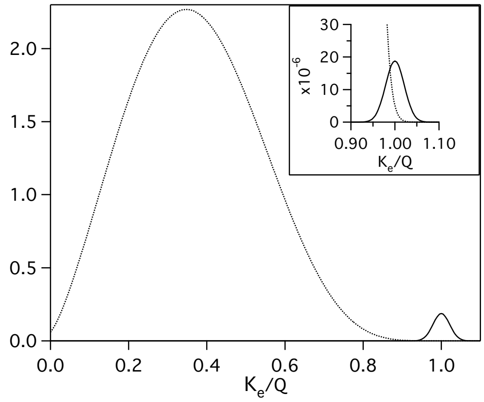

Figure 1: $2\nu\beta\beta$ and $0\nu\beta\beta$ two electrons sum energy spectra. $2\nu\beta\beta$ is a continuum between 0 and $Q_{\beta\beta}$, while $0\nu\beta\beta$ is a peak centered at $Q_{\beta\beta}$. In the inset is shown that a good energy resolution is needed to disentangle the two spectra. The y-axis scale and the $0\nu\beta\beta$ relative peak height are arbitrary.

half-life corresponding to the minimum number of signal events observable above background at a given statistical significance (expressed in Gaussian standard deviation(n_σ). For experiments in which the background counts scales as the total mass of the detector it can be expressed as

$$S^{bkg} = \frac{\ln 2}{n_\sigma}\frac{N_A}{\mathbf{A}}\epsilon\eta\sqrt{\frac{Mt}{b\Delta E}}$$

where N_A represents the Avogadro number, **A** the atomic mass number of the studied nucleus, ϵ the detection efficiency, η the isotopic abundance of the $\beta\beta$ emitter, M the detector mass in kg, t the experiment livetime, b the background in the ROI, and ΔE the energy resolution. The most significant parameters are the ones under the square root: M, t, b and ΔE. From the experimental point of viewsome limitations arise on these parameters: b turns to be the most important parameter to work with to improve the sensitivity, since the other ones are quite limitated: for example, M could not be larger than some tons, t generally is supposed to be in the interval $5 \div 10$ y and ΔE is somehow fixed once the detection technique is selected. Moreover, if the background is low enough to reach the zero background limit, the sensitivity formula dramatically improves:

$$S^{0bkg} = \frac{\ln 2}{n_\sigma}\frac{N_A}{\mathbf{A}}\epsilon\eta Mt \qquad (1)$$

Isotope	$Q_{\beta\beta}$ [keV]	Iso. Abb. [%]
^{48}Ca	4274	0.187
^{76}Ge	2039	7.4
^{82}Se	2997	8.7
^{100}Mo	3034	9.6
^{116}Cd	2814	7.5
^{130}Te	2528	33.8
^{136}Xe	2458	8.9
^{150}Nd	3368	5.6

Table 1: Q-values and isotopic abundances of the principal candidates for a $0\nu\beta\beta$ experiment [3].

2. The LUCIFER experiment

2.1. The isotope selection

Double beta decay can occur only in a ten of isotopes. Looking for the one to use in an experiment, one must take into account the Q-value of the reaction and the isotopic abundance of the atom (see Tab.1). From an experimental point of view, isotopes with $Q_{\beta\beta} > 2615$ keV are preferred, since above this energy (the ^{208}Tl photoelectric line) the naturalγ radioactivity is reduced by a factor ~ 100. According to these criteria, ^{82}Se ($Q_{\beta\beta} = 2997$ keV, $\eta = 8.7$ %) and ^{100}Mo ($Q_{\beta\beta} = 3034$ keV, $\eta = 9.6$ %) result to be two of the best choices. These isotopes show other good features, like the possibility to grow crystals with a large mass fraction of these elements and the possibility to artificially enrich them to increase the $\beta\beta$ emitter number.

2.2. The technique

The bolometric technique is particularly feasible for the $0\nu\beta\beta$ search, even if many others have been proposed and used [4]. Bolometers are calorimeters operating at low temperature, in which the energy deposited by a particle is converted into phonons and is detected as a temperature variation. In this approach, the energy deposited by a single particle into an energy absorber (weakly connected to a heat sink) determines an increase of its temperature T (~ 0.1 mK/MeV). This variation corresponds simply to the ratio between the energy released by the particle and the heat capacity of the absorber. The only requirements are therefore to operate the device at low temperatures (less than 0.015 K), in order to make the heat capacity low enough, and to have a sensitive thermometer coupled to the energy absorber. The thermometer is usually a thermistor, a resistive device with a steep dependence of the resistance on the temperature.

The energy absorbing part of the detector is made usually of diamagnetic, dielectric crystal in order to avoid electron contributions to the specific heat in addition to the Debye term, proportional to T^3 at low temperatures.

Semiconductor thermistors consist usually of Ge or Si small crystals with a net dopant concentration slightly below the metal-insulator transition. This implies a strong dependence of the sensor resistivity on the temperature at low temperatures, where the Variable Range Hopping conduction mechanism dominates.

The reasons why the bolometric technique is very suitable can be summarized as follows:

- crystals can be grown with $\beta\beta$ emitter directly inside: high detection efficiency ($75 \div 80\,\%$),
- energy resolution ca be of the order of per mille,
- high radio-purity is reachable,
- scalability is quite simple,
- different compounds can be used to study different isotope (necessary for a convincing $0\nu\beta\beta$ observation).

Huge efforts are needed to reduce as much as possible all the background sources: cosmic radiation is reduced by placing the experiment in underground laboratories, the environmental radioactivity by using dedicated shieldings, the shielding radioactivity with an accurate material selection and cleaning and the bolometers contaminations by means of a radio-pure crystals growth.

The bolometric experiment CUORE-0 was built paying attention to all these points. Crystals production method, cleaning procedures of the materials and the final assembly line were validated and will be used for the future experiment CUORE [5]: . Using these precautions, CUORE-0 reached a background of 2×10^{-2} counts/keV/kg/y in the LUCIFER ROI [6]. It has been demonstrated that the principal source of background for these experiments consists of degraded α particles located on the crystal surface or on the tower material facing the crystal, that do not release all their energy in the bolometer, but only a random fraction of it [7, 8]. To reach the zero background limit for LUCIFER of 10^{-3} counts/keV/kg/y, a more effective background reduction is needed.

A solution to this problem comes from the scintillating bolometers (see Fig. 2). When the bolometer crystal is an efficient scintillator at low temperatures, a small but significant fraction of the deposited energy (up to a few %) is converted into scintillation photons while the remaining dominant part is detected in the form of heat. The emitted light can be measured by a light detector facing the scintillating bolometer [9]. The idea to use a bolometer as light detector was first developed by Bobin et al. [10] and then optimized [11, 12] for Dark Matter searches. The first simultaneous detection of phonons and photons was achieved more than a decade ago by the Milano group with a CaF_2 bolometer and a conventional Si photodiode as light detector, developed as a pilot device for the search of $0\nu\beta\beta$ in ^{48}Ca.

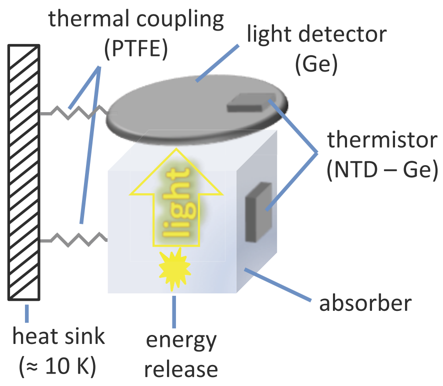

Figure 2: Schema of (scintillating) bolometer operation. An energy release by a particle interaction raises the crystal temperature. Then this temperature variation is measured by a thermometer, a neutron transmutation doped (NTD) Ge thermistor. The accumulated heat is subsequently dissipated by means of a coupling to a thermal bath. In a scintillating bolometer less than 1 % of the total energy goes into scintillation photons. To detect this light and discriminate the α background, a second bolometer is faced to the main one and operated as light detector.

Nowadays it is clear that the effective method to detect scintillation photons in such a very low temperature environment is to develop a dedicated bolometer, in form of a thin slab, opaque to the emitted light and provided with its own phonon sensor. This auxiliar bolometer [14], a Ge thin slab, is positioned very close to a flat, optically polished, side of the main scintillating bolometer. In order to maximize the light collection, it is convenient to surround the whole set-up with a reflecting foil. Using such light detectors, one can produce a scatter plot with on the x-axis the energy of the event and on the y-axis the detected light.α and β/γ particles have different light yield, so it is possible to identify and reject the α background [13] It is possible to define a quantity, called Quenching Factor, that quantifies the separation between the α and the β/γ band: $QF = \frac{\alpha_{detected\,light}}{\beta/\gamma_{detected\,light}}$ for events of the same energy.

Crystal	$Q_{\beta\beta}$ [keV]	Emitter mass [kg]	QF	FWHM [keV]
ZnSe	2997	≈ 9.8	4.2	16.5
$ZnMoO_4$	3034	≈ 6.2	0.14	7

Table 2: Principal characteristics of two samples of the two alternatives for LUCIFER. ZnSe shows a $QF = 4.2$, while smaller than 1 was expected. The FWHM at $Q_{\beta\beta}$ for ZnSe is evaluated using the correlation between the light and the heat channels (while for $ZnMoO_4$ the resolution remains the same also using this approach). QF and FWHM may slightly vary from sample to sample.

2.3. Detector layout

LUCIFER (Low background Underground Installation For Elusive Rates) will search for $0\nu\beta\beta$ of ^{82}Se with ZnSe scintillating bolometer or, as alternative, the $0\nu\beta\beta$ of ^{100}Mo with $ZnMoO_4$ scintillating bolometers. It will be hosted in the underground Laboratori Nazionali del Gran Sasso (3650 m. w. e.) near L'Aquila, Italy. The detector will consists of 36 cylindrical crystals (45 mm diameter, 55 mm height), enriched at 95 %, each one equipped with a Ge disk (44 mm diameter, 180 μm thickness) operated as a light detector. It will be arranged in a tower of 9 floors with 4 crystals per floor. In Tab.2 the fundamental characteristics of two samples of the two possible choice for the experiment are summarized.

2.3.1. ZnSe scintillating bolometers

Several ZnSe bolometers have been assembled and tested, with different physical and bolometric properties. The one presented here is a 430 g crystal, that shows an excellent particle identification. As can be seen in Fig.3, these bolometers exhibit a peculiar QF larger than 1. At the moment ZnSe is the unique known compound having this unexpected feature. This apparently minor characteristic can hide a risk: if the light is not correctly detected, an α particle could "fall" in the β/γ region of the scatter plot. To solve this problem, it is possible to exploit the informations coming from the light detector pulse shape, as visible in Fig.4.

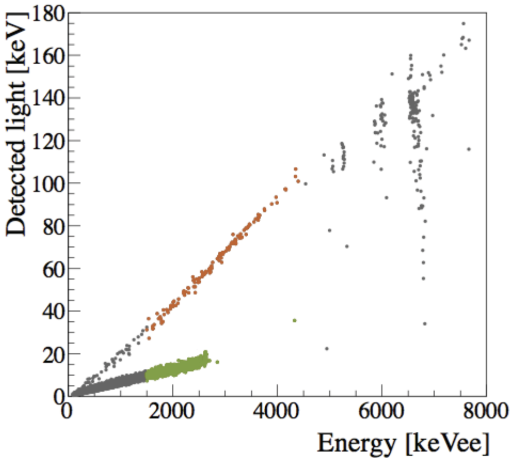

Figure 3: Scatter plot of the detected light vs the energy (revealed in the heat channel) obtained for the ZnSe bolometer. This compound is the unique known to show a $QF > 1$, i.e. α events (in orange) emit more light than β/γ ones (in green). Image from [15].

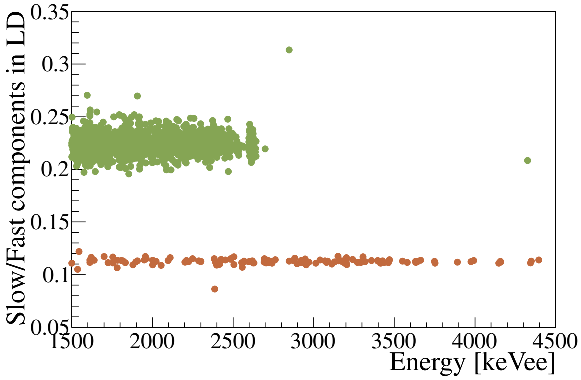

Figure 4: Using a parameter that is sensitive to the shape of the pulses collected by the light detector, it is possible to discriminate α background even in case the light from ZnSe is not correctly detected and the event "falls" in the signal region. α events are highlighted in orange, β/γ ones in green. Image from [15].

Analyzing the data of this bolometer, it is clear that an effective α rejection is achievable, minimizing the background where ^{82}Se $0\nu\beta\beta$ signal is expected: no events occur in the ROI during 524 h of background measurement.

Crystal contaminations are 3×10^{-4} counts/keV/kg/y in ^{238}U and 3×10^{-3} counts/keV/kg/y in ^{232}Th, while an external background of the order of 10^{-3} counts/keV/kg/y is reliable. This leads, for a 5 y measurement of a ≈ 20 kg detector, to expect 1 count of background in the ROI, meaning that a zero background detector is attainable.

2.3.2. $ZnMoO_4$ scintillating bolometers

Several $ZnMoO_4$ crystals were measured in our facility, with masses ranging from 30 to 330 g. The results presented here are from the largest one, which fundamental parameters are in Tab.2. This bolometer features a very good particle identification, as shown inFig.5, given the very low QF and very narrow bandwidth of α and β/γ populations. The energy resolution of 7 keV at the Q-value is an excellent result, like the very low

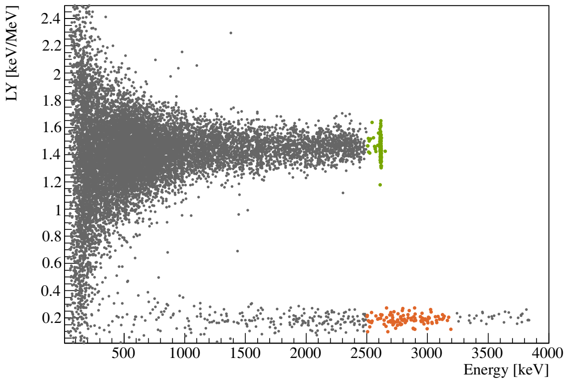

Figure 5: Scatter plot of the light yield vs the energy (revealed in the heat channel) in the $ZnMoO_4$ bolometer. With a $QF = 0.14$ and narrow bandwidths, α (in orange) and β/γ particles (in green) are well separated. Image from [16].

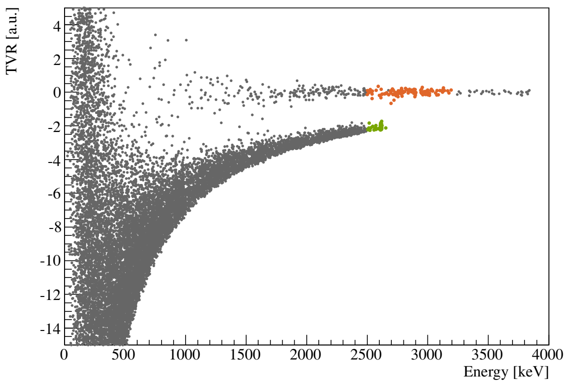

Figure 6: $ZnMoO_4$ bolometers are capable to discriminate α (in orange) and β/γ interactions (in green) using a parameter, named TVR, related to the pulse shape in the heat channel. Image from [16].

contaminations (measured in a 524 h run): $< 10\,\mu$Bq/kg in ^{238}U and ^{232}Th, that lead, also in this case, to a background free detector. In particular the β/γ region of the scatter plot, where the ^{100}Mo $0\nu\beta\beta$ should fall, is empty of events.

As last remark, we noticed in this bolometer the pulse shape depends on the interaction nature, meaning that it is possible to discriminate α particles using directly the $ZnMoO_4$ without the help of the light detector (Fig.6).

2.4. Sensitivity

Considering that a zero background detector is achievable, sensitivity is given bi Eq. 1. Corresponding values ($T^{0\nu}_{1/2}$) for 5 or 10 y of measurement of ZnSe and

crystal	live time [y]	90 % C.L. $T^{0\nu}_{1/2}$ [10^{26} y]	$\langle m_{\beta\beta}\rangle$ [meV]
ZnSe	5	0.6	65 ÷ 194
ZnSe	10	1.2	46 ÷ 138
$ZnMoO_4$	5	0.3	60 ÷ 170
$ZnMoO_4$	10	0.6	42 ÷ 120

Table 3: 90 % C.L. sensitivity ($T^{0\nu}_{1/2}$) for 5 and 10 y of ZnSe and $ZnMoO_4$ and relative effective neutrino masses ($\langle m_{\beta\beta}\rangle$).

$ZnMoO_4$ are listed in Tab.3 for a 90 % C.L. These values are comparable with the 90 % C.L. sensitivity of 5 y of CUORE, an experiment that will have a mass more than one order of magnitude higher: 0.95×10^{26} y.

The last column in Tab.3 refers to the neutrino effective mass, which is related to the sensitivity by:

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}\left|M^{0\nu}\right|^2 \left(\frac{\langle m_{\beta\beta}\rangle}{m_e}\right)^2$$

where $G^{0\nu}$ is the phase space factor, $M^{0\nu}$ the Nuclear Matrix Element and m_e the electron mass. Explorable values of $\langle m_{\beta\beta}\rangle$ range from some tens of meV to two hundreds of meV.

3. Conclusions

Neutrino mass and nature are still open questions. Neutrinoless double beta decay, if observed, could give them an answer. Among the various possible techniques to search for this decay, the scintillating bolometer's one results to be particularly indicated, allowing to discriminate between α background and β/γ signal. This makes possible to achieve the zero background limit and consents to have a sensitivity that linearly increases with experimental livetime and detector mass.

LUCIFER is a next generation experiment demonstrator, that will search for the $0\nu\beta\beta$ of ^{82}Se or^{100}Mo with, respectively, ZnSe or $ZnMoO_4$ scintillating crystals. Using these compounds for a ≈ 20 kg detector in 5 y of measurement in a background free condition, the sensitivity on $0\nu\beta\beta$ will be of the order of 10^{26} y, corresponding to a neutrino effective mass of the order of 100 meV.

Acknowledgments

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